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Problems of the Reliability of Man in Spacecraft Control Systems*

P. K. Isakov, V. A. Popov and M. M. Sil'vestrov

Man or automatic devices in the investigation of space, this is the problem that has long been discussed in the press. At the present time an even larger number of researchers is approaching a unique solution of this problem. The solution consists in a judicious combination of the properties inherent in man and automated systems.

The inclusion of a human being in a spacecraft control system increases its reliability and in some cases reduces the weight and bulk of the equipment. Moreover, in order to ensure the operational reliability of pilotless flying spacecraft it is necessary to incorporate a high level of equipment redundancy, that is, to provide for a multiple reserve of systems and instruments. But if the work of an operator is combined with only a single or double reserve, it is almost certain that systems of the craft will function without failure for a considerable period [4]. But if the operator is also provided with the means to repair the faulty parts of the control system, the reliability will become very high, being governed essentially by the reliability of the operator. A method in which the reliability of spacecraft control systems in enhanced by rational combination of the functional capabilities of man and the characteristics of the equipment is considerably more effective than any purely technical method of ensuring reliability.

The "operator-spacecraft" system is a closed multiloop system. In such a system an operator can fulfill the role of the logic and computer devices, of the /6
meter of the control process parameters, of the amplifying, integrating, and differentiating links, of the control formulation system, etc.

The amount of information presently available on the operational characteristics of an astronaut controling a spacecraft and the research instrumentation during actual space flights is still insufficient. As is to be expected, however, the experimental characteristics of various work operations performed by astronauts in flight are often very different from those on earth.

For instance, the time spent by cosmonaut B. B. Yegorov to perform operations with the medical equipment in the "Voskhod" was 1.5 to 2 times greater than he spent on earth. Without doubt, this was a result of specific space-flight conditions affecting the cosmonaut-operator.

Because the amount of information obtained during flight in space is insufficient, it is especially necessary to make wide use of ground test equipment. At the same time, investigation of the reliability and efficiency characteristics of human operation in test devices on the ground, both from the standpoint of principle and of actual conditions, requires that "man-machine" models be set up so that not only the control process itself can be simulated, but also the specific conditions that contribute to creating any given state of a human operator.

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Let us mention the basic problems that can be solved by means of such simulations.

1. Analysis of the dynamics of the control process of a system in which a man participates. In such a study the given equations of the plant and control system are solved on computers in a natural time scale.

2. Solution of the problem of synthesis of the control system. This problem reduces to choosing the structure of the variable part of the system, its characteristics, the values of the parameters, and the rational form of the information model, on the basis of the given technical conditions and of the known properties of the operator.

3. Experimental investigation of the system decided on. In such investigations some of the system elements are actual ones, along with their properties; the operation of the rest of the elements is reproduced by a computer in a natural time scale according to the given equations.

4. The experimental study of the response of the system under laboratory conditions, and of its efficiency, when the operator is subjected to simulated specific flight factors (overwork, hypodynamia, isolation, noise, vibration, ambient gaseous medium, illumination, etc.).

5. Formulation of the qualities of the operator in accordance with the requirements of the control system. This problem is solved by training operators on simulators and special trainers as well as by using special drug-induced effects. /7

The control process is simulated with the aid of a computer. An analog-digital complex is used to solve complicated problems. Signals are fed from the output of the simulator to an information model, that is, to an indicator and signaling system. Specific flight factors can be simulated by means of dynamic test arrangements which imitate the external flight conditions, the life-support systems, and also by means of special devices which make it possible to elicit in the organism reactions which are similar to the reactions of the organism to the flight factors being applied.

The system is designed to record the variables of the control process, the responses of the operator, and his physiological functions. The efficiency and reliability of a control system in which the human participates is evaluated by analyzing the indications from the dynamics of the control process, errors in the steady-state and forced modes, the final result of the control, the energy expended in the control process, the quantity and nature of the incorrect actions of the operator, and changes in the physiological functions of the operator.

The psychophysiological features of human activity in controlling a spacecraft and its equipment depend to a significant degree on the systems with which he is working. In space flight it is necessary to perform control operations both with a time deficit and a time surplus. A surplus of time is the reserve of time available to the operator in performing a certain task; it is considerably greater than the total time required to carry out the operations associated with the completion of the task. A time surplus may be available for controlling the angular motions of the craft, which can be done either by active or passive means. The force moments generated by the ambient medium are used in passive stabilization of the spin of a space ship. The force moments arising as a result of interaction between the craft and the ambient medium are small, and therefore the spin period

will be large, from a few tens of minutes (when using the gravity and magnetic field gradient of the earth or the aerodynamic forces of orbital flight) to several hours (when using the radiation pressure of the sun). If active means are used (jet engines, interior rotating masses, etc.), the spin rate increases, but in order to economize on power reserves, it remains about several degrees per second, and the time of the transient process may be of the order of several minutes. In this case there is also a surplus of time. But when the spacecraft is carrying out such flight steps as approach and docking, reentry into dense /8
atmospheric layers, touchdown, etc., the astronaut has to work under a time deficit situation. Time deficit and information overload may cause sharp deviations in the activity of an operator, reducing operational reliability. The primary events under such conditions are gaps in incoming signals and delayed response to the increasingly complex situation. When information arrives too slowly and the control processes take too much time (surplus of time), the human operator begins to be distracted from controlling the given process, and this may lead to incorrect actions and deterioration of the control process. Surplus of time and a monotonous situation lower the functional level of the human analyzer systems. Experimental study of operational activities has shown that in normal flight of "Vostok" the cosmonaut works with the instrument package without a time deficit. The instrument reading time does not limit the execution of operations in any case.

From 2.2 to 3.1 sec are required, while controlling the spacecraft, to determine the numerical value of one of the parameters characterizing the environmental state of the cabin (the temperature, oxygen content, carbon-monoxide gas, etc.). This period depends on the form of the face of the instrument and on its location on the instrument panel. The mean time required to perceive light signals fluctuates between 0.8 to 1.2 sec, depending on the color and intensity of the signal and its location on the signal panel [1]. The accuracy of manual control depends on the information model, on the location of the image of the parameters being read relative to the eyes of the operator, and on the indication systems within the operator's field of view. The accuracy of control by a reference point is greater when the deviation of the point is determined relative to a vertical reading line rather than to a horizontal one. This was observed in control experiments on a simulator when the operator had to carry out the following operations: place one circle concentric to another, keep a luminous dot or a symmetrical figure in the cross-lines on an election-beam tube, keep a cross symmetrical when the two lines forming the cross were movable relative to each other, so as to correspond with the control dynamics, and also when reading the indications of instruments with vertical and horizontal scales. For example, the accuracy of mounting a circle on a vertical control channel was less by a factor of 1.6 than on a lateral channel. The accuracy of controlling the location of a spot on the screen of an electron-beam tube in conformity with the spin dynamics of a spaceship in a vertical control channel (in the axial plane) was less than in a lateral control channel by a factor of 2. The accuracy with which the cross bars were kept symmetrical during manual control of the spin stabilization of a spacecraft /9
was better in the vertical case by a factor of 2.2 than in the lateral case. Of definite interest is the study of the time required to perceive signals indicating the magnitude and rate of mismatch in the control process when using an electron-tube indicator. The experiments showed that when the luminous spot deviated from the cross-hairs of the indicator by more than 4 mm, the average time it

took to determine the error was 0.9 sec; when it deviated by 1 mm, the time of perception was 1.2 sec. When the speed of motion of the image was more than 1 mm per sec, the time required to determine the sign of the derivative of the deviation was about 1 sec and was almost independent of the speed. At a lower speed the average time it took to determine the sign of the mismatch derivative increases, reaching 4.2 sec at a speed of 0.1 mm per sec.

As the tasks of space flight become more complex, a piloted spacecraft will become saturated with an even greater number of indicators, signal devices and control units. The nature of space flight, the fact that it takes place in phases, make it absolutely necessary that the astronaut receive information from all or from a majority of the instruments and signal devices, and that not all the control levers be necessary in every given step. The operational reliability of the operator in spacecraft systems increases if we employ the principle whereby the operator need handle the various indicators, signal devices and control units only step by step, in accordance with the tasks to be performed.

The particular features of space flight conditions, such as weightlessness, considerable overwork during launch and descent, intermittent time deficits and time surpluses in performing operational tasks, the fact that the flight is carried out in phases, the multiple sources of information in the control system, all these factors determine how we must construct the information model and the control consoles, the scientific research equipment, and the operational instruments. In the case of spacecraft flight of a team consisting of several men, the reliability of the "man-spacecraft" system depends to a considerable degree on how the control functions are distributed among the crew members. For example, experiments have shown that if the functions of controlling eight specific points of the process are rationally distributed between two operators, the quality of control improves by a factor of 2.5 as compared with control by a single operator, and the percentage of unsuccessful control actions decreases by one half.

As indicated above, the reliability of the man-spacecraft system can be studied in an appropriate manner if various factors (noise) act on the operator.

In doing so, we should strive to have the state of the operator approximate as closely as possible the state that may be observed under normal and extreme flight conditions. Let us indicate several examples of the nature of such noise effects.

While working in the simulator the operator was presented with experimental illusions of rolling. This was done by exciting the vestibular analyzer with direct current (from 2 to 5 milliamps). During the period the rolling illusion was effective, the time it took to perceive the signals of the paravisual indicators increased by 2 to 3 seconds. Also noted was a characteristic interruption of coordination of control motion. /10

When the model cabin was subjected to noise of up to 90 db and a temperature of 40—45° C, pronounced changes in the quality of control were noted only after the operator had been subjected continuously to 3 to 4 hours of these conditions. In particular, the three-dimensional control of the spacecraft (in the simulator) deteriorated by a factor of 1.2.

A study of the effect of prolonged isolation and hypokinesia on the activity of an operator in transmitting information by means of a teletype instrument [2] and in controlling the altitude of a spaceship showed that pronounced deterioration of

the efficiency was noted in the first few days of isolation and hypokinesia. The quality of orientation became worse by a factor of 1.5 as compared with the initial compared data. On the third day the quality of operation was restored almost to the original level. It should be emphasized that an analogous tendency was observed in actual tendency flight.

The operational reliability of a human is also determined by the way in which he handles his work under complex conditions, e.g., when the operator must control the operation of various systems, answer transmitted inquiries, etc., while performing the main task of control. In this case psychological noise of peculiar nature occurs, causing the most significant failures in the quality of control. In the experiments the operator was presented with an additional task in which he was to turn away from his control functions in order to read instrument indications, to count light signals, etc. The necessity of switching tasks and distributing his attention resulted in deterioration of the quality of three-dimensional control of the motion of the plant according to an instruction device by a factor of 1.6 to 1.8, and the time required to perceive paravisual indicators increased from 2-3 to 8-10 sec [3].

When an operator had to control eight distinct parts of the control process while being interrogated by radio on the readings of indicators and signal devices, the quality of manual three-dimensional control of spacecraft motion deteriorated by a factor of 1.7 as compared with control in the absence of noise.

The above presentation indicates that an effective approach to estimating human reliability in spacecraft control systems consists in the broad use of simulators of the dynamics of the control process and of the state of the operator, approximating as close as possible his state under normal and extreme flight conditions.

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